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## *TECHNOLOGY STATUS REPORT*

# Fuel Cells:
# a promising technology for the next millennium

Ministry of the Environment

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# TECHNOLOGY STATUS REPORT

# Fuel Cells:

# a promising technology for the next millennium

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Prepared by:
Paul Bakker
Environmental Partnerships Branch
Ministry of the Environment

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## Executive Summary

Ground-level ozone is a serious air quality problem in Ontario. The Windsor-Quebec corridor has been designated as one of Canada's three ozone non-attainment areas. Emissions of nitrogen oxides ($NO_x$) and volatile organic compounds (VOCs) are the two precursors of ground-level ozone. $NO_x$ emissions are also one of the two dominant precursors of acid rain. Air quality in Ontario's large urban centres presents a major problem. To a large degree, this is a result of emissions from internal combustion engines in vehicles. In 1994, vehicles produced more than 65% of Ontario's $NO_x$ emissions and 30% of its 142,000,000 tonnes of carbon dioxide ($CO_2$) [1]. At the same time, power plants emitted close to 10% of $NO_x$ and 12% of $CO_2$ emissions in Ontario [1].

A key goal of Ontario's Smog Plan is to reduce both $NO_x$ and VOCs emissions to 45% of their 1990 levels by the year 2015 [2]. Ontario is committed to assist Canada in meeting the national climate change objectives [30]. In order to achieve Ontario's proposed reduction targets for ground-level ozone and reduce provincial greenhouse gas emissions, it will be necessary to accelerate the acceptance and use of fuel cell technologies in Ontario.

Fuel cells convert chemical energy directly to electrical energy using a continuous electrochemical process. This chemical energy is converted into electrical energy with high efficiency, negligible pollution and little noise. This report reviews the status of fuel cell technology development. It also discusses potential fuel cell applications in Ontario and benefits to the province.

Fuel cells offer a number of environmental advantages over internal combustion engines and traditional thermal generating systems. The most important of these include reduced atmospheric emissions and higher energy conversion efficiencies. Fuel cells are considered an "engine of change" with the potential to make hydrogen energy and a sustainable energy economy a reality [35].

This report discusses the technology status of a number of fuel cell technologies and areas requiring further technology development. This report also provides estimates of expected benefits for Ontario from the potential fuel cell activities generated by several applications.

Fuel cells have emerged in the last decade as one of the most promising new environmental technologies. Fuel cell technologies are expected to make a significant environmental impact on our lives in the next 5-10 years. Important applications of fuel cell technologies are expected to include zero emission vehicles and clean stationary power plants.

In addition to the impressive environmental benefits, fuel cell technologies can have a very positive economic impact in Ontario. The manufacturing of fuel cell components, plant equipment, and hydrogen supply/storage systems is expected to create new industries and add growth to existing industries and services. Currently, there are at least five companies in Ontario developing the capability for manufacturing fuel cell related systems and components.

If fuel cell vehicles and power plants comprise 1% of Ontario's 1994 on road light-duty vehicle fleet and electric power demand by 2015, gaseous emissions (i.e. $NO_x$, CO, $CO_2$) would be reduced by more than 735,000 tonnes/year. Potential fuel cell activities generated by just these two applications would represent an estimated annual combined economic activity in Ontario of more than $180 million/year and associated employment potential would exceed 1,800 new Ontario jobs by 2015.

Stakeholders, including government, can help speed up the use of new fuel cell technology in Ontario in a number of ways including:

- providing realistic and complete information on fuel cell technologies, emissions, economics, employment potential and well documented case studies; and

- identifying cost effective opportunities for appropriate new fuel cell technology applications in Ontario.

## 1. Introduction

Fuel cells offer unique strategic advantages for environmentally clean electricity production. Fuel cell technologies are expected to make a significant environmental impact on our lives in the next 5-10 years. The applications of fuel cell technologies are expected to include zero emission vehicles and clean stationary power plants.

Fuel cells convert chemical energy directly to electrical energy using a continuous electrochemical process. This chemical energy is converted into electrical energy with high efficiency, negligible pollution and little noise. The basic fuel cell has no moving parts. Fuel cell energy conversion efficiencies are potentially much higher than those for internal combustion engines (ICE) and for thermal electricity generation systems. Fuel cells have the capability of co-generating electricity and heat. Their ability to maintain high efficiency and part load in the small capacity range is also of note.

Fuel cells can be powered by hydrogen, methanol, ethanol, propane, natural gas and coal syngas, to name a few. When fuelled with pure hydrogen, fuel cells produce only electricity, water and heat. When reformed natural gas, coal syngas or methanol are used $CO_2$ is also produced. However, $CO_2$ emissions on a kg/MWh basis will be lower than those generated by conventional power sources. The $NO_x$ emissions from stationary fuel cell installations are very low, typically 10% of the emissions from turbines and 1% of the emissions from internal combustion engines. Fuel cells already satisfy the strict environmental requirements of the state of California.

Fuel cells are being developed in many countries for use in electric power generation and providing electric vehicles. This report reviews the status of fuel cell technology development. It also discusses potential fuel cell applications in Ontario, as well as environmental and economic benefits to the province.

## 2. Technology Description

Fuel cells are direct energy conversion devices; they convert chemical energy directly to electrical energy. Since they do not utilize a thermomechanical combustion process, they are not Carnot-cycle limited. That is, efficiency is not a function of operating temperature. Fuel cells are like a continuous battery. In fact, some of the early literature refers to them as a "fuel battery". A fuel cell will operate continuously as long as it is supplied by a fuel source and an oxidant. For stationary power plants, the fuel is usually reformed natural gas (gasified coal in the future), and the oxidant is air. The fuel cell type is defined by its electrolyte composition.

The fuel cell system is composed of two or three major components: the fuel processor (for indirect cells), the fuel cell and the power conditioner. In the case of hydrocarbon fuels (e.g. natural gas), the fuel processor converts the raw fuel to a hydrogen rich gas stream. The fuel is catalytically reacted with steam to generate hydrogen, carbon monoxide (CO) and carbon dioxide ($CO_2$) in a process known as steam reforming. Coal is processed using a non-catalytic gasification process. These products are then fed into the fuel cell. Some types of cells require the removal of the $H_2S$, CO and/or $CO_2$ from the feed stream, while others can use CO as a fuel along with the $H_2$.

Fuel cells can be described as either direct or indirect and are further classified according to combination of fuel, oxidant and electrolyte used. Direct cells are able to use the supplied fuel directly, that is, without external reforming. A fuel cell fuelled with pure hydrogen would be considered a direct cell.

Indirect cells require the fuel to be converted from its original form in a reforming process. For low and medium temperature (<250°C) fuel cells, the reforming process to produce hydrogen rich gas is external to the cell. High temperature fuel cells can use byproduct heat to reform fuels directly within the cell and stack. Achievable efficiencies are lower for indirect systems because energy is required for the reforming process. Efficiencies as great as 60%-70% may be achievable for a hydrogen air fuel cell. Somewhat lower efficiencies result when a carbon based fuel (natural gas, methanol, syngas) is used (e.g., a natural gas powered phosphoric acid fuel cell).

A different category of fuel cells, considered to be semi fuel cells, utilize metal as fuel. The aluminum air fuel cell (AAFC) is a good example of this type of fuel cell. The AAFC utilizes aluminum as fuel.

Single fuel cells are only capable of generating low voltage DC power, typically less than 1 Volt. A fuel cell power source is comprised of a series of electrochemical cells, arranged in series to form a unit module or stack. The stack size and electrical output are designed to yield a cost effective system for a range of applications. The cell area and current density (amps/ft$^2$) determine the current (amps), and the number of cells determine the voltage; the product is the power capability of the fuel cell stack. These stacks/modules are then placed in a series and/or parallel configuration to meet the application and power conversion requirements.

Hydrogen is the primary electro-active fuel. The gas reformer is a conversion device required to convert hydrocarbon fuels to a hydrogen rich fuel stream. Since fuel cells produce DC electricity, a power conditioning unit (i.e. an inverter plus transformer) is required to convert DC to AC power. This modular feature permits fuel cell units to be added as needed to match load growth, in preference to installing a large costly power generating unit. Since fuel cells are not combustion devices $NO_x$ emissions are very low. With a minimum of moving parts they are expected to have long life and low noise levels. The basic operational system components are shown in Appendix B, Exhibit 1.

The most common types of fuel cells, of current technical and commercial interest, are listed below in descending order of their developmental status as follows:

| Type of Fuel Cell | Development Status |
|---|---|
| • Alkaline Fuel Cell (AFC) | Commercial for space and military applications |
| • Phosphoric Acid Fuel Cell (PAFC) | Commercial for power plants |
| • Molten Carbonate Fuel Cell (MCFC) | Early demonstration |
| • Proton Exchange Membrane Fuel Cell (PEMFC) | Prototype and early demonstration |
| • Solid Oxide Fuel Cell (SOFC) | Development and prototypes |
| • Direct Methanol Air Fuel Cell (DMAFC) | Research |

An external gas reformer is used to supply hydrogen gas for alkaline, phosphoric acid and solid polymer fuel cells. The MCFCs and SOFCs, operating at high temperatures, can directly use natural gas or methanol by internally converting these gases to hydrogen. The electrochemical reactions for different fuel cells are shown in Appendix B, Exhibit 2.

Using fuel cells to power electric vehicles, as an alternative to the internal combustion engine (ICE), is intended mainly to achieve:

- greater fuel economy and the utilization of alternative transportation fuels such as methanol, natural gas and hydrogen;
- a significant reduction in emissions of CO, $CO_2$, $NO_x$, unburned hydrocarbons, aldehydes and particulate matter from transportation vehicles; and
- extending the range of travel by electric vehicles when fuel cells are used in conjunction with batteries.

There are five fuel cell technologies being considered for use in transportation applications [3,4]:

- Alkaline Fuel Cell (AFC)
- Direct Methanol Air Fuel Cell (DMAFC)
- Phosphoric Acid Fuel Cell (PAFC)
- Proton Exchange Membrane Fuel Cell (PEMFC)
- Solid Oxide Fuel Cell (SOFC)

These technologies have unique combinations of attributes, which make them attractive for different applications. AFCs, PAFCs and PEMFCs absolutely require direct hydrogen entering the fuel cell. This means that, when used in transportation applications, either hydrogen fuel must be stored on board the vehicle or an on board hydrocarbon fuel reformer is required. Performance comparisons for some of these fuel cell types are summarized in Appendix A, Table 1.

PAFC is the most advanced option. Its 200 kW rating is consistent with the output required for bus and truck applications. A 500-1000 kW fuel cell system has been developed and is being used in stationary power plants (1-11MW), providing a starting point for development of locomotive units.

A number of auto manufacturers are supporting PEMFC development (most notably, DaimlerChrysler, Ford, GM, Honda, Volvo, VW). PEMFC technology is also being developed for various space and undersea applications in capacities ranging up to 25kW. The ongoing U.S. Department of Energy (DOE) supported Light-Duty Vehicle Program is based on the use of PEMFC technology because of its high power density and compatibility with rapid load cycling operation.

SOFC technology has been demonstrated at the 25 kW size for stationary applications and is being evaluated for several different applications due to its potential for simplified on board fuel processing, high power density and low costs. DMAFC is the least developed of the fuel cell technologies and is being considered for transportation applications for the same reasons as SOFC, namely the potential for better performance at lower costs.

The efficiency with which hydrogen is converted into electricity ranges between 45%-65%, depending on fuel cell technology and operating conditions. Fuel cell powered vehicles (FCV) are projected to attain efficiencies of 35%-55% after thermal and parasitic power losses are taken into account [3]. Efficiencies for current internal combustion engine vehicles (ICEV) are only about 18%. Thus, FCVs can achieve a per vehicle reduction in energy consumption of at least 50%.

The near term market for FCVs will be driven by environmental considerations, namely zero emission vehicle (ZEV) requirements. The long term market prospects for FCVs, however, will be determined by economics where its competitiveness will be measured against the then current vehicle alternatives which also meet environmental, safety and other requirements.

In areas with severe air quality problems, such as southern California, it is now recognized that dramatic emissions reductions from even the best current practices will be required to meet regulatory requirements.

An FCV operated on methanol can achieve emission levels for CO, $NO_x$, and non-methane organic gas (NMOG) substantially less than those levels established for the California Ultra Low Emission Vehicle (ULEV) standards. Appendix B, Exhibit 5 illustrates projected emissions of FCVs relative to current and future standards. If hydrogen is used for fuel the FCV will be a zero emission vehicle (ZEV). A ZEV fuelled by hydrogen produced from non-fossil electricity represents a substantial reduction in combined ground-level ozone and regional acid and greenhouse gases.

The focus of near term markets for fuel cell vehicles will be urban areas having severe air quality problems. The negligible emissions from fuel cells in both light-duty and heavy-duty vehicles (buses, trucks, urban train systems, trolleys) will make a major contribution toward reducing transportation sector emissions to meet stringent future regulatory limits.

In stationary power plants, fuel cells offer the following advantages:

- on site power source for remote locations;
- power source for industries where waste or by product fuel gases are available;
- modular construction, flexible capacity;
- shorter transmission lines, reduced transmission costs;
- high energy efficiency, co-generation of electricity and heat;
- environmental benefits due to negligible emissions and lower noise levels;
- substantial reductions in greenhouse gas ($CO_2$) emissions;
- relatively short capital construction period; and
- power from alternative fuel sources such as natural gas, methanol, waste hydrogen and gas from coal gasification.

Although it is anticipated that fuel cells will be utilized across the broad spectrum of utility power generation, initial market entry units will be smaller scale. Thus, they should be sited close to the load or within an area of load growth in urban and/or residential environments. Being close to the load reduces transmission losses, further enhancing their already high efficiencies.

Fuel cell types considered to be the most promising for utility and non-utility electricity generation are as follows [3,5,6]:

- Phosphoric Acid Fuel Cell (PAFC)
- Proton Exchange Membrane Fuel Cell (PEMFC)
- Molten Carbonate Fuel Cell (MCFC)
- Solid Oxide Fuel Cell (SOFC)

## 2.1 Phosphoric Acid Fuel Cell (PAFC)

PAFCs utilize hydrogen as fuel and air (oxygen) as an oxidant, with phosphoric acid serving as the electrolyte. The phosphoric acid cell may be used in conjunction with a variety of clean, light hydrocarbon fuels such as natural gas, naphtha or methanol with the appropriate reforming process. Electrical conversion efficiencies of 35%- 45% have been achieved for hydrocarbon fuels. PAFC systems represent the most highly developed state of fuel cell technology with commercialization projects initiated in both the U.S. and Japan.

Concentrated phosphoric acid is used for the electrolyte in this fuel cell, which operates at 160-220°C. At lower temperatures, phosphoric acid is a poor ionic conductor and CO poisoning of the Pt electrocatalyst in the anode becomes more severe. The relative stability of concentrated phosphoric acid is high compared to other common acids, consequently the PAFC is capable of operating at elevated temperatures. In addition, the use of concentrated acid minimizes the water vapour pressure so water management in the cell is not difficult. The matrix used to retain the acid is usually SiC, and the electrocatalyst in both the anode and cathode is Pt. This latter system, tested by B.C. Hydro in a 40 kW module, and by Ontario Hydro in a 200 kW ONSI unit, operated with an average electrical generation efficiency of 40% lower heating value (LHV).

## 2.2 Proton Exchange Membrane Fuel Cell (PEMFC)

The electrolyte in a PEMFC is an ion exchange membrane (fluorinated sulphuric acid polymer) which is an excellent proton conductor. The only liquid in this fuel cell is water, thus corrosion problems are minimal. Water management in the membrane is critical for efficient performance; the fuel cell must operate under conditions where the byproduct water does not evaporate faster than it is produced because the membrane must be hydrated. Because of the limitation on the operating temperature, usually less than 120°C, $H_2$ rich gas with little or no CO is used. Higher Pt and Pt alloy loadings than those used in PAFCs are required in both the anode and cathode. Ballard's leading edge PEMFC technology has been selected by DaimlerChrysler for its advanced zero emission fuel cell compact car, NECAR 4.

## 2.3 Molten Carbonate Fuel Cell (MCFC)

MCFCs operate at temperatures of approximately 650°C (e.g. 600-700°C) where the alkali carbonates that compose the electrolyte become molten. MCFCs can use reformed light hydrocarbon fuels or coal syngas. Although the natural gas can be reformed within the fuel cell systems by using the steam and heat produced by the fuel cell reaction, one MCFC design uses an external fuel reformer. Efficiencies of up to 60% can be achieved when fuelled by natural gas.

The electrolyte in this fuel cell is primarily a combination of alkali (Li, Na, K) carbonates, which is retained in a ceramic matrix of $LiAlO_2$. At 600-700°C the alkali carbonates form a highly conductive molten salt, with carbonate ions providing ionic conduction. At the high operating temperatures in MCFCs, Ni (anode) and nickel oxide (cathode) are adequate electrode materials, and noble metals are not required.

The electrical conversion efficiency of a commercial MCFC is expected to be in excess of 50%. If co-generation of steam is added to the package, the overall efficiency rises to as much as 66%. If low quality heat is also recovered, via hot water extraction, overall thermal efficiency would be higher.

## 2.4 Solid Oxide Fuel Cell (SOFC)

SOFCs utilize a solid electrolyte and operate at approximately 1000°C. SOFCs can be fuelled using reformed hydrocarbons or syngas. Because of the high operating temperature, it is possible to use natural gas directly with some special internal reforming equipment. Natural gas can be reformed within the fuel cell by utilizing the steam and heat produced by the fuel cell reaction. Efficiencies of about 50% can be achieved when fuelled by natural gas. SOFCs offer the attractive feature of high temperature steam production that could result in highly efficient, clean and comparatively economic combined cycle power plants.

The electrolyte in this fuel cell is a solid, nonporous metal oxide, usually $Y_2O_3$ stabilized $ZrO_2$. Ionic conduction by oxygen ions takes place at the cell's operating temperature (e.g. 950-1,000°C). Typically, the anode is made of Co-$ZrO_2$ or Ni-$ZrO_2$ , and the cathode is Sr doped $LaMnO_3$.

### 2.5 Alkaline Fuel Cell (AFC)

AFC has already been used extensively in space technology and for some special military applications in submarines and armoured vehicles. In the future AFC may be used for civil transportation purposes if hydrogen becomes readily available.

A disadvantage of AFC is its sensitivity to carbon dioxide. The fuel and the oxidizing agent usually contain carbon dioxide which reacts with the alkaline electrolyte, producing carbonates. The fuel must therefore be pure hydrogen and the air supply containing oxygen must be free of carbon dioxide.

Another disadvantage is the high cost. Extensive research work remains to be carried out in order to construct an economically viable fuel cell for civilian applications. Although AFC has reached an advanced level of development it remains very expensive. Nevertheless, there are well developed plans for the use of AFC in buses.

### 2.6 Aluminum Air Fuel Cell (AAFC)

Fuel Cell Technologies Ltd., of Kingston, Ontario, has developed an aluminum air fuel cell (AAFC). AAFC is an electrochemical device that produces electricity cleanly, silently and safely without combustion. AAFC generates power through an electrochemical reaction between the metal, once placed in a saline or alkaline solution, and oxygen from the air. Electricity is produced as the aluminum oxidizes. Targeted applications range from emergency power supplies and main/auxiliary power systems for electric vehicles, boats, submarines and submersibles [7]. The development work has produced a number of products that are now being marketed and installed, including:

- telecommunications reserve batteries
- aluminum-oxygen underwater propulsion systems
- components for marine propulsion batteries

The company has also successfully tested its small prototype cell on an electric vehicle test rig.

## 3. Status of Fuel Cell Developments

### 3.1 Canada

In Canada, a number of companies are involved in fuel cell related work, including Ballard Technologies, Ontario Hydro Technologies (OHT), Fuel Cell Technologies, Astris-Energi, H Power Enterprises of Canada (HPEC), and Hydrogenics Corporation. The fuel cell technologies being developed by these companies include PEMFC, SOFC, AFC and AAFC. Stuart Energy Systems Inc. is developing hydrogen fuelling stations and has started marketing its residential hydrogen supply system [11].

In addition to this research and development (R&D) work, a number of field demonstrations of PAFC were carried out in Canada. For example, B.C. Hydro and Energy, Mines and Resources Canada (EMR) successfully demonstrated the operation of a 40 kW PAFC stationary power plant. The same fuel cell was tested for on site co-generation of electricity and hot water at an aquatic centre in the town of Delta, B.C. Hydro Quebec has also been involved in the demonstration of PAFCs for electric power generation.

Ontario Hydro operated and monitored a 200 kW PAFC power plant at its Markham Centre (near Toronto). The unit, installed in mid 1994, operated on pipeline natural gas [18]. The Ontario Hydro project, completed in 1997, received funding support from Consumers Gas, the former Ontario Ministry of Environment and Energy, NRCan and the Canadian Electrical Association (CEA). The fuel cells for these Canadian projects were initially supplied by International Fuel Cells Inc. (IFC), and more recently by its subsidiary, ONSI Corp.

R&D activities in Canada include:

- Since the early 1980's, Ballard Technologies Corp., of Vancouver, B.C., has been working on the development of solid polymer fuel cells for vehicular and stationary applications such as hydrogen fuel cell buses and submarines. Ballard is currently considered the world leader in the field of PEMFC technology. The company has obtained energy densities ten times greater than those reported for PACFs. Ballard Power Systems is currently evaluating PEMFC on commuter buses. By 1996, Ballard had delivered over 50 PEMFCs and fuel cell systems to customers in North America, Europe and Japan [10]. Recently, the Chicago and Vancouver transit authorities each purchased three full scale, hydrogen fuel cell powered buses from Ballard.

- Ballard's work in the fuel cell area has attracted investment by three major companies. In 1997 Daimler-Benz invested nearly $200 million in Ballard's fuel cell work. The Ford Motor Company joined forces with Ballard and Daimler-Benz to accelerate the development of fuel cells for trucks and cars, and in late 1997 announced its decision to invest $600 million in the alliance. Also, GEC Alsthom NV invested $53 million in Ballard Generation Systems to manufacture 250 kW fuel cell stationary power plants. Ballard plans to commercialize fuel cell systems for buses by 2001, and for stationary power plants by 2005.

- Development work for various applications, supported consistently by the Canadian government, has included commercial developments such as a fuel cell powered commuter bus and small (10-30 kW) stationary generator sets fed with hydrogen/natural gas. In the mid 80's, the former Ontario Ministry of Energy provided funding support to Dow Canada for testing a 10 kW Ballard PEMFC for in plant power generation. The fuel cell used hydrogen produced as a by product from the chlor-alkali process at Dow's Sarnia plant.

- Ontario Hydro Technologies (OHT) and Siemens-Westinghouse are conducting development work on Siemens-Westinghouse's SOFC systems, using a pressurized cycle, to improve the performance and economics. The work is being carried out at OHT's research facilities in Toronto and has produced very promising results. The initial project received funding support from a consortium comprised of CEA, GTC, the former Ontario Ministry of Environment and Energy, Consumers Gas, Union Gas, British Gas and NRCan [26]. OHT's test work with Siemens-Westinghouse is ongoing.

- Astris-Energi (Mississauga) is engaged in developing, manufacturing and marketing AFCs, including work on the storage of hydrogen gas as a metal hydride. In 1996, this company started a joint development project with Westinghouse SRC to produce prototype fuel cell units to power golf carts using Astris-Energi's AFCs.

- With the assistance of an Ontario Ministry of Energy grant, the former Alupower Canada Inc. (now Fuel Cell Technologies, Kingston), started the development of a 6 kW AAFC to be used in combination with a lead acid battery for extending the driving range of an electric vehicle. Fuel Cell Technologies is continuing its development work on AAFCs, as well as AFCs, to further improve the performance and economics of these systems for a variety of applications.

- Hydrogenics Corporation (Toronto) is conducting R&D into hybrid fuel cell generators. The company has made great strides in applying fuel cells as a stationary power source that can operate at very low temperatures (e.g. -40°C).

- H Power Enterprises of Canada Inc. (HPEC), founded in 1997, is developing and commercializing PEMFCs for stationary applications. HPEC's particular interest is in residential PEMFC applications.

- Stuart Energy Systems (Toronto) is a leading firm in developing innovative hydrogen supply/ storage technologies relevant to the emerging fuel cell market [11]. Stuart specializes in connecting electricity to fuel markets (stationary and mobile). Stationary applications include linking distributed renewable (remote) electricity to energy storage and then fuel supply to fuel cells. Stuart's principle focus is supplying hydrogen fuel to fuel cells in transportation markets. The company is cooperating with Ballard, B.C. Hydro and B.C. Transit to provide hydrogen fuel to Ballard's three demonstration buses in Vancouver. Stuart is revolutionizing the hydrogen fuel supply business through its Fleet Fuel Appliance (FFA) concept. The FFA is an enabling technology for hydrogen fuel cell vehicles. It does so in a manner which connects a "non peak time of use" electricity supply to the appliance to produce hydrogen by water electrolysis. Stuart has also developed a hydrogen supply system for residential use, the Personal Fuel Appliance (PFA). The PFA, now available for demonstration, enables the owner to fill up a car or truck overnight with hydrogen.

- A one day fuel cell conference and a two day hydrogen conference were held in Toronto, in 1996 and 1997 respectively [20,22]. These events were co-sponsored by the former Ontario Ministry of Environment and Energy and NRCan, as well as a number of companies and utilities, including Ontario Hydro Technologies, Ballard Power Systems and Electrolyser Corporation.

## 3.2 Other Countries

Virtually all developed countries have a fuel cell development program in progress. The four major types of fuel cells involved are PAFCs, MCFCs, SOFCs and PEMFCs. Each type has preferred applications but there is considerable overlap. For commercial stationary electric power production PAFC systems represent the most highly developed fuel cell technology. PEMFCs appear headed for eventual application in vehicle propulsion and may provide competition to PAFC for stationary power plants (less than 1MW).

All fuel cell types are environmentally friendly compared with conventional applications of fossil fuel combustion. In the U.S., Canada, Europe and Japan, governments have provided a major impetus and considerable funding for R&D programs on fuel cell systems. For example, by 1995 the U.S. government had contributed more than $750 million US to fuel cell R&D [5]. The Canadian government has contributed more than $4 million annually to hydrogen and fuel cell R&D [8].

Around the world, there are more than 120 fuel cell systems either in operation or under development for stationary power installations. In addition, a number of PEMFCs are being field tested for vehicular applications. These systems have a modest total output of about 45 MW (Appendix A, Table 2). In 1995 it was estimated that annually about $200 million US was being spent by about 15 countries for fuel cell development and that R&D activity had been increasing rapidly during the past five years [5,9]. The leading developers are the U.S. and Japan. The U.S. Department of Energy's (DOE) annual fuel cell funding is close to $100 million for stationary power sources and vehicular applications. While development in the U.S. has been funded primarily by the DOE, additional sources of funding include Electric Power Research Institute (EPRI), Gas Research Institute (GRI) and other government agencies. In Canada, development to date has been funded primarily by NRCan and Department of National Defence (DND) [7,8].

For electric power production, major candidates are PAFCs, MCFCs and SOFCs. Examples of R&D efforts in the U.S. and throughout the world include:

- International Fuel Cells Inc. (IFC), based in upstate New York, has been actively developing PAFCs and MCFCs. ONSI, an IFC subsidiary, has been developing small stationary PAFCs. By the end of 1997 ONSI had delivered more than 100 small stationary PAFC units (i.e. 200kW modules) with a projected capital cost of $3,000 per kW, about twice the desired cost.

- The major developers of MCFCs are now Energy Research Corp. (ERC), a subsidiary of International Fuel Cells Inc., and M-C Power. ERC and M-C Power are funded primarily by DOE [6,31]. In January 1995 M-C Power received an additional DOE grant to produce a 1 MW MCFC power plant in cooperation with Bechtel Corp., Stewart & Stevenson Services Inc. and the Institute of Gas Technology.

- M-C Power had an unsuccessful start up of a 250 kW unit up in Brea, California, at the Unocal Science & Technology Center. Another 250 kW unit was commissioned in 1997 at the Miramar Naval Air Station in San Diego. These units are considered pre-commercial demonstration plants [25]. The projected cost based on the demonstrations is $1,680 U.S. per kW, a figure that has attracted the interest of the power industry currently in the throes of deregulation and looking for new technology to lower its production costs to a more competitive level.

- Siemens-Westinghouse Power Corporation (Siemens-Westinghouse) concentrates on the development of pressurized SOFCs. The company's commercialization emphasis will reportedly be based on an integrated pressurized combustion turbine (SOFC-CT) combined cycle system [17]. The estimated power plant performance ranges from 60%-70% for plants with a net power output of 3-10 MW. Testing at Siemens-Westinghouse has progressed to the point where groups of SOFC cells have been operated for over 69,000 hours (over eight years). Self supported SOFC cells are now used in generators, which improves performance and reduces cost by eliminating the porous support tube. Cell lengths of up to 150 centimetres have been produced and tested with a degradation rate of less than 0.5%/1000 hours. The 24 kW Joint Gas Utility (JGU) unit with 576 cells was operated for more than 13,000 hours with a cell degradation rate of less than 0.1%/1,000 hours. The conceptual design of a 300 kW integrated gas turbine/fuel cell power plant has been completed. Several 100 kW tests are planned. The

first 100 kW generator was fabricated in 1997 and testing at a utility site in the Netherlands commenced in late 1997.

- H-Power Corporation (U.S.) is developing PEMFC technology. H-Power has focussed on developing fuel cell systems for stationary power plants and heavy vehicles, including hydrogen conversion and storage technology, based on its sponge iron process. The company is actively involved with the development and manufacturing of fuel cell technologies for alternative uses. In 1997, the company founded H Power Enterprises of Canada.

- Energy Partners Inc. (EP) produced a "Green Car" in 1992. Since its inception there have been very few operating demonstrations of this vehicle. Formerly a subcontractor to Ford under DOE's vehicular fuel cell program, EP is currently working with several partners to develop PEM fuel cell vehicles.

- Allied Signal focuses its PEMFC R&D, started in 1992, on zero emission vehicle (ZEV) applications and is a subcontractor to Chrysler. It plans to produce most of the fuel cell system components itself [10].

- Germany is making a major effort to develop a hydrogen economy and a government/ industry consortium has built a hydrogen technology and fuel cell test facility in Bayern. The consortium includes Siemens, Deutsch Aerospace and Varta. DaimlerChrysler is also working on a PEMFC for automobiles in a joint program with Ballard Power Systems of Vancouver. In March 1999 DaimlerChrysler introduced its early prototype hydrogen FCV, NECAR 4. This FCV uses Ballard's PEMFC system and is powered by liquid hydrogen. DaimlerChrysler plans to have NECAR 4 in limited production by 2004. The company also expects to be in a position to introduce NECAR 5, a methanol FCV, by late 1999.

- Japan has invested heavily in PAFCs, although it is also interested in other types of fuel cells. The Japanese have formed several joint ventures with U.S. companies and are aggressively pursuing fuel cell development, including a stake in M-C Power by Ishikawajima-Harima Heavy Industries and a stake in IFC by Toshiba. Toshiba and Fuji Electric Co. are developing a 1 MW and a 5 MW power plant, respectively, both based on PAFCs. They also have two small 25 kW demonstration plants based on Siemens-Westinghouse SOFC technology.

- Japan's fuel cell programs are being conducted by the Japanese government in cooperation with utilities and industries through the New Energy & Industrial Development Organization. This organization has the task of coordinating the development of PAFC, PEMFC, SOFC and MCFC types and providing development data to the appropriate manufacturing sectors of the Japanese economy. The government is involved in cost sharing for the development in which about one third of the purchase cost of an on site co-generation plant based on PAFCs is being borne by the government.

- Other countries are progressing well in their R&D efforts on alternative fuel cell types. For instance, a Dutch-Belgian consortium known as Elenco has developed a 14 kW AFC for a Volkswagen van and is also working on a larger unit to power a bus. Siemens Ltd. is working on a fuel cell for the European space shuttle program and submarines.

## 4. Economics of Fuel Cell Technologies

The major drawback to acceptance and accelerated development of the technology is the current high cost of fuel cell devices.

## 4.1 Fuel Cell Vehicles

Several studies have estimated the overall costs of mass producing fuel cell vehicles [4,32]. These analyses suggest the incremental cost of FCVs probably would be no more than several thousand dollars. These studies estimate that the cost of a gaseous hydrogen fuel cell, an energy storage device to provide peak power, compressed gas canisters and all auxiliaries would total about $8,000-12,000 US. After taking credit for the displaced internal combustion engine, drive train and emission control system, mass produced fuel cell cars would reportedly cost $2,000-5,000 more than gasoline powered vehicles. However, PEMFCs now cost more than $3,000/kW. Within several years this could probably be reduced to $500/kW. Most PEMFC proponents talk about costs of less than $200/kW in full production. This is the reason why cost remains a serious problem for light-duty vehicles. As a result, fuel cell powered light-duty vehicles are not expected to be fully commercialized before 2007. Buses and heavy-duty trucks will be commercialized earlier. DaimlerChrysler announced in March 1999 that they expect to have their hydrogen fuel cell car, NECAR 4, in limited production in 2004.

Reportedly, a FCV would be relatively inexpensive to operate because of reduced maintenance requirements and higher fuel efficiency. Because of the higher energy efficiency of FCVs the cost of fuel (e.g. methanol, hydrogen) per kilometre is estimated to be substantially less than for gasoline powered vehicles.

## 4.2 Power Plants

Fuel cell power plants have significant potential for application in distributed electricity generation. However, fuel cell market acceptance will be dependent on providing a competitive advantage over commercially available generating technologies, including reciprocating engines, gas turbines and micro turbines.

In the near term, the PAFC is the closest to commercialization in electric utility applications. First generation fuel cells will be in the 200 kW to 3 MW range for modular dispersed power plants to perform load following duty. These small plants are likely to be sited in urban areas since emissions and noise levels are low. The projected installed cost for these units will be about $1,500 US/kW at the time of market entry and about $1,000 US/kW later with automated production [6]. At the projected future capital cost level of $1,000/kW, PAFCs reportedly compete with coal fired power stations, although the estimated total unit energy cost of PAFCs at 7-8 cents/kWh is still higher than from coal fired power plants.

Vendors of fuel cell power plants that have been in this field the longest (e.g. ONSI, MC-Power) have established it is reasonable to anticipate their programs will be able to provide power plants at prices of about $1,500 US/kW at the time that sales volumes will reach 100-400 MW/year. In the U.S., ONSI has now received more than 125 orders from a number of gas and electric utilities for the sale of 200 kW capacity PAFC power plants. Each power plant is priced at $600,000 US and includes a natural gas reformer and a DC to AC power inverter. ONSI claims an electrical efficiency of 40%, and an overall energy efficiency of 70% from a PAFC operating in co-generation mode.

MCFCs claim to be more cost competitive than PAFCs and are considered more suitable for larger capacity applications in competition with coal fired and gas turbine combination power plants. Conceptual MCFC designs have been prepared by the developers for 250 kW to 3 MW plants. Design studies predict 50%-60% efficiency (HHV basis) with small scale units on natural gas and for larger plants integrated with coal gasifiers. Manufacturing cost estimates indicate that MCFC

stack selling prices of less than $300 US/kW may be feasible at modest production rates (200 MW per year). These results increase confidence that overall development targets are achievable.

For the long term (after 2010), the goal is to provide modular central stationary plants that, when integrated with coal gasifiers, will produce electricity with high efficiency and low emissions. These plants are projected to have a heat rate of 6,800 BTU/kWh and total airborne emissions (ie. $NO_x$, $SO_2$, hydrocarbons and particulates) of less than 0.025 kg/MWh.

### 4.3 Fuels Processing and Hydrogen Storage

A key issue currently facing fuel cells for transportation applications is the non-existent hydrogen supply infrastructure. If hydrogen were widely available, fuel cells would be easier to commercialize. The introduction of fuel cell vehicles must be coordinated with a strategy for developing the necessary fuels. On board storage of hydrogen results in the simplest fuel cell vehicle propulsion system. However, hydrogen's low energy density requires a large storage volume to achieve adequate range. With on board reforming, fuel cell powered vehicles can carry liquid fuels in tanks similar to those in today's vehicles. Fuel reformers can extract hydrogen from fuel such as methanol, ethanol, and natural gas, and provide the same range capability as today's vehicles. Although reforming gasoline is more difficult than methanol, both reformed methanol and reformed gasoline are considered potential transition fuels for fuel cell vehicles. Further fuel reformer development is focussed on reducing the size, weight, cost and dynamic response capabilities of the various reformer systems.

The current costs of producing and using hydrogen are well in excess of those costs associated with conventional transportation fuels. However, technological development of hydrogen fuel use is proceeding at a rapid pace. Hydrogen can be produced from a number of different feed stocks, and in different ways. From an environmental perspective, the most attractive production method is the electrolysis of water. Currently, steam reforming of natural gas is the most widely used, cost effective and efficient larger scale hydrogen production process. If hydrogen is to be produced on a smaller scale, it can be generated on site at a public/fleet refuelling station or residence. Both methane reformers and electrolysis units are practical alternatives on a small scale. Residential refuelling at a home hydrogen production unit is reportedly an attractive option for early adoption. At this small scale, electrolysis is expected to have favourable economics. [11, 32]

Success of fuel cells for transportation applications will depend upon an effective hydrogen supply. Stuart Energy Systems is focussed on this matter by connecting electricity to fuel markets and creating a long term shift in how electricity is made and supplied, as well as enabling convenient and practical fuel supplies for fuel cells. Hydrogen production from non-fossil electricity provides an “energy storage” means for electricity. This has substantial long term consequences for the introduction of non-fossil electricity sources, such as renewables, which provide intermittent electricity.

## 5. Potential Benefits to Ontario

Ground-level ozone, a major compound of urban smog, is a serious air quality problem in Ontario today. Ground-level ozone is caused by two precursor pollutants, nitrogen oxides ($NO_x$) and volatile organic compounds (VOCs). The Windsor-Quebec corridor has been designated as one of Canada's three ozone non-attainment areas [12]. $NO_x$ emissions are also one of the two dominant precursors of acid rain. In 1994, over 65% of the $NO_x$ emissions in Ontario were generated by vehicles [1,23]. Power plants generated close to 10% of Ontario's $NO_x$ emissions.

A key goal of the Ontario Smog Plan is to reduce emissions of both $NO_x$ and VOCs to 45% of their 1990 levels by the year 2015 [2]. In 1990, Ontario's $NO_x$ emissions were 659,000 tonnes.

Carbon monoxide (CO) is an odourless poisonous gas and an air pollutant which is produced due to incomplete combustion of fuel. Annual emissions in Ontario of CO exceed 3,100,000 tonnes [1]. The transportation sector accounts for over 65% of these emissions.

Carbon dioxide ($CO_2$) is a greenhouse gas. In 1994, Ontario's $CO_2$ emissions were 142,000,000 tonnes [1]. About 30% of $CO_2$ was generated by vehicles and 12% by stationary power generation. Ontario is committed to assisting Canada meet the national climate change objectives [30].

Fuel cells offer a number of environmental advantages over internal combustion engines and traditional thermal generating systems. The most important of these include reduced atmospheric emissions and higher energy conversion efficiencies. Fuel cells are considered an "engine of change" with the potential to make hydrogen energy and a sustainable energy economy a reality [35].

Atmospheric emissions, including $NO_x$, $SO_2$, CO, $CO_2$, hydrocarbons (HC) and particulates, from fuel cells are much lower than those associated with fossil fuel electricity generating systems. Emissions will depend on the fuel and the fuel cell technology used.

As one of the most promising new environmental technologies, applications of fuel cell technology represents an attractive potential market in Ontario.

Assessments of application opportunities for fuel cells in Ontario, B.C. and Canada have been reported and opportunities are impressive [10,13,14,15]. Assuming reductions in capital costs (e.g. to $1,500Cdn/kW for power plants and $240Cdn/kW for light-duty vehicles), some market segments are in the multi-billion dollar bracket. Studies cover a variety of segments, including industrial, commercial, residential, power utility and transportation sectors. The potential economic activity for Ontario is substantial. The commercialization of Ballard's fuel cell technology can serve as a good example of the anticipated impact on the provincial economy [10]. The manufacture of Ballard fuel cells is expected to generate an additional $593 million in economic activity for B.C.'s economy by 2005. It is also expected to create over 6,000 new B.C. jobs by 2005.

Electric vehicles powered by fuel cells offer the promise of substantial emission reductions relative to ICEVs, including reductions of typically 90% $NO_x$, > 75% CO and > 60% $CO_2$ [2, 32, 33]. Assuming an EV market penetration of 1% of the 1994 on road light-duty vehicle fleet in Ontario by 2015, the following total annual transportation related emissions reductions would be realized: 1,900 tonnes $NO_x$, 7,200 tonnes CO, and 454,300 tonnes $CO_2$. In 1994, Ontario's on road light-duty gasoline fuelled vehicle fleet consisted of about 6 million vehicles. This segment of the vehicle fleet is projected to increase to over 8.2 million by 2015.

Fuel cells, being modular in nature, can be targeted for a wide range of power supply applications in Ontario, including remote applications, on site co-generation applications (including residential/ commercial sector applications) and utility applications. Commercial building co-generation is expected to provide some of the best market entry opportunities with allowable costs as high as $2,000 US/kW [21].

Fuel cells for stationary power generation appear to be an attractive option for Ontario Hydro [13]. Fuel cells offer a practical, clean approach to the utilization of fossil fuels in electricity generation. While not sustainable, this approach is better environmentally than other fossil fuel generation technologies. $NO_x$, CO and $CO_2$ emissions from fuel cell installations are typically only 10% for $NO_x$, 1% (or less) for CO and 60% ( or less) for $CO_2$ of the emissions from conventional plants. Ontario Hydro has estimated the upper limit of fuel cell power plant potential for Ontario at 800 MW by the year 2014 [13].

Ontario Hydro's R&D is currently aimed at further developing and demonstrating promising fuel cell systems such as Siemens-Westinghouse's pressurized SOFC. Assuming that fuel cell power plants will contribute 200 MW of the electricity supply mix in Ontario by the year 2015, this will represent a reduction in stationary power plant emissions of 274,000 tonnes per year. 200MW represents approximately 1% of Ontario's 1994 power demand; Ontario's power demand in 1994 was 149 million MWh. [16].

If fuel cell vehicles and power plants comprise 1% of Ontario's 1994 on road light-duty vehicle fleet and electric power demand by 2015, annual gaseous emissions (i.e. $NO_x$, CO, $CO_2$) would be reduced by more than 735,000 tonnes/year. Potential fuel cell activities generated by just these two applications would represent an estimated annual combined economic activity in Ontario of more than $180 million/year and associated employment potential would exceed 1,800 new Ontario jobs by 2015. If market penetration were increased to 2% by 2020, gaseous emissions in Ontario would be reduced by more than 1,470,000 tonnes/year. The estimated environmental and economic impacts of these two potential applications in Ontario are summarized in Appendix A, Table 3. Estimated emission reductions are further described below.

**Estimated Emission Reductions (tonnes/year)**

| Type | Year 2015 (1% market penetration) | Year 2020 (2% market penetration) |
|---|---|---|
| $NO_x$ | 3,300 | 6,600 |
| CO | 12,600 | 25,200 |
| $CO_2$ | 721,750 | 1,443,500 |

Overall fuel cell application potential, and hence economic impact, in Ontario is substantially greater than described above. Economic development that will occur around fuel cells must be viewed in context of the entire energy system. This includes not only the fuel cell stack, but also the components needed to make up the power plant fuel supply (compressors, controls, reformers), packaging of the application and its integration with end use.

For Ontario companies, providing the "balance of plant" (all of the fuel cell system components, excluding the fuel cell stack) could represent a very attractive business opportunity. The "balance of plant" reportedly represents more than half the cost of the total system. Ontario will likely benefit, as it has in the past with the auto industry, from assembly and parts supply.

When fuel cells mature, like any other component, manufacturing will be subcontracted to generic part suppliers. Opportunities to develop and manufacture FCV motors (e.g. Elettra Technology Inc., Hamilton), motor controllers, charging systems, power inverters (e.g. Inverpower Controls Ltd., Burlington), fuel storage and reformers, gas cleaning equipment, refuelling systems and many other components,represent a substantial opportunity for Ontario companies.

## 6. Stakeholders

Potential stakeholders in Ontario include electric and gas utilities, equipment suppliers, engine manufacturers, manufacturers of hydrogen supply and storage systems, and developers and manufacturers of fuel cell systems and components.

Ontario companies currently developing and/or manufacturing fuel cell systems and/or components include:

- Astris-Energi
- Fuel Cell Technologies
- Stuart Energy Systems
- Inverpower Controls
- Hydrogenics

Other companies and organizations, either conducting or supporting fuel cell related development in Ontario include :

- Ontario Hydro Technologies
- Enbridge Consumers Gas
- University of Toronto (CHES)
- NRCan/CANMET
- Department of National Defence
- University of Ottawa (ESTCO)
- McMaster University

## 7. Impediments

Impediments to the development and commercialization of fuel cells include high cost, limitations on materials of construction and unproven high risk technology.

A key issue that must be addressed from a competitive standpoint is the capital cost of fuel cell power plants and engines [6,25]. Most American vendors of fuel cell power plants have established $1,500 US/kW as their capital cost target. This was done several years ago when coal fired plants cost about $1,500/kW and natural gas combined cycle systems cost about $600 US/kW. Over the past 3-4 years these costs have fallen. U.S. vendors are now reviewing their cost targets. Their main competition is from central stationary combined cycle power plants. Ballard expects to bring 250 kW PEMFC units (for stationary power plants) to market at about $1,000US/kW.

It has been claimed that manufacturing costs of fuel cells for electric vehicles must be brought down to at least $200 US per kilowatt before the fuel cells can compete with internal combustion engines. Further fuel cell development is required to achieve adequate performance, packaging and cost for use in automobiles including:

- size and weight reduction;
- manufacturing cost reduction;
- start up and response time reduction;
- durability in an automotive environment; and
- fuel storage, conditioning and delivery.

Further R&D and demonstration work is needed to overcome the risks and barriers mentioned above. To realize the potential benefits of fuel cell technologies in Ontario, especially cleaner emissions from electric vehicles and power plants, continued government support will be required.

## 8. Conclusions

Fuel cells have emerged in the last decade as one of the most promising new environmental technologies. Fuel cells are considered an "engine of change" with the potential to make hydrogen energy and a sustainable energy economy a reality [35].

Ground-level ozone is a serious air quality problem in Ontario. The Windsor-Quebec corridor has been designated as one of Canada's three ozone non-attainment areas. Emissions of $NO_x$ are one of the two precursors of ground-level ozone. Air quality in Ontario's large urban centres presents a major problem. To a large degree, this is a result of emissions from internal combustion engines in vehicles. In 1994, more than 65% of the $NO_x$ emissions in Ontario were generated by vehicles.

Fuel cell technologies are expected to make a significant environmental impact on our lives in the next 5-10 years. Important applications of fuel cell technologies are expected to include zero emission vehicles and reduced emissions from stationary power plants. In addition, commercial building co-generation is expected to provide some of the best market entry opportunities. Successful utilization of fuel cells could enable increased penetration of electricity from renewable energy sources.

In addition to impressive environmental benefits, fuel cell technologies can have a very positive economic impact in Ontario. The manufacturing of fuel cell components, plant equipment and hydrogen supply/storage systems are expected to create new industries, as well as add growth to existing industries and services. There are currently at least five companies in Ontario developing capability to manufacture fuel cell related systems and components.

If fuel cell vehicles and power plants comprise 1% of Ontario's 1994 on road light-duty vehicle fleet and electric power demand by 2015, annual gaseous emissions (i.e. $NO_x$, CO, $CO_2$) would be reduced by more than 735,000 tonnes/year. Potential fuel cell activities generated by just these two applications would represent an estimated annual combined economic activity in Ontario of more than $180 million/year and associated employment potential would exceed 1,800 new Ontario jobs by 2015. If market penetration were increased to 2% by 2020, gaseous emissions in Ontario would be reduced by more than 1,470,000 tonnes/year.

A major drawback to acceptance and accelerated development of fuel cell technology is the current high cost of fuel cell devices. Another key issue facing transportation fuel cells is the non-existent hydrogen supply infrastructure.

In order to achieve Ontario's proposed reduction targets for ground-level ozone and reduce greenhouse gas emissions, it will be important to accelerate the acceptance and use of fuel cell technologies in Ontario. Stakeholders, including government, can help speed up the use of fuel cell technologies in Ontario in a number of ways including:

- providing realistic and complete information on fuel cell technologies, emissions, economics, employment potential and well documented case studies; and

- identifying cost effective opportunities for appropriate new fuel cell technology applications in Ontario.

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## APPENDIX A

**Table 1 - Performance Comparisons for Fuel Cell Types** (Reference # 27)

| Fuel Cell Type | Proton Exchange Membrane | Alkaline | Phosphoric Acid | Molten Carbonate | Solid Oxide |
|---|---|---|---|---|---|
| Operating temperature (Celsius) | 80° | 80° | 200° | 650° | 1000° |
| Power/density (watt/kg) | 340-1500 | 35-105 | 120-180 | 30-40 | 15-20 |
| Efficiency | 40%-60% | 40%-60% | 40%-47% | 50%-57% | 45%-50% |
| Time to operation | Seconds | Minutes | 2-4 hours | >hours | >10 hours |
| Fuel source | Pure H2, reformed methanol, nat. gas | Pure H2 | Reformed nat. gas | Nat. gas, syngas | Nat. gas, syngas |
| Platinum used | Yes | No | Yes | No | No |

Table 2 - Major World Fuel Cell Activity (Reference # 24)

| Country | *Fuel Cell Status* | | | | Approximate Operating Capacity (KW) [in 1994] |
|---|---|---|---|---|---|
| | Phosphoric Acid | Molten Carbonate | Solid Oxide | Proton Exchange | |
| Austria | ③[1] | | | | 200 |
| Australia | | | ①② | | |
| Canada | ③[1] | | | ①②③ | 325 |
| Denmark | ③[1] | ①③[1] | ①② | ① | 200 |
| Finland | ③[1] | | | ① | 200 |
| France | | ① | ① | ① | |
| Germany[2] | ③[4] | ①② | ①② | ①② | 800 |
| Italy | ①③[1] | ①② | ① | ①② | 1,500 |
| Japan | ①②③[4]④ | ①② | ①③[5] | ① | ~40,000 |
| Korea | ①③[4] | ①② | ① | | 450 |
| Netherlands | | ①② | ① | | |
| Norway | | | ①② | | 2 |
| Spain | ③[3] | ①② | | | 200 |
| Sweden | ③[1] | ① | | | 200 |
| Switzerland | ③[1] | | ①② | | 200 |
| United States | ①②③④ | ①②③ | ①②③ | ①②③ | ~4,500 |

① - Research
② - Development
③ - Demonstration
④ - Near commercial or commercial sales

Notes:
1 - U.S. power plant(s).
2 - 100 kW alkaline fuel cell submarine system.
3 - Japanese power plant(s).
4 - U.S. and Japanese power plants.
5 - Westinghouse (U.S.) SOFC modules.

Table 3 - Estimated Impact of Two Types of Potential Fuel Cell Applications in Ontario by 2015 and 2020

| Fuel Cell Application | Installed Cost [3] (M$) | New Jobs Created [4] | Emission Reduction (tonnes/yr) [5] |
|---|---|---|---|
| I. **Fuel Cell Power Plants (FCPP), Capacity** [1] | | | |
| By year 2015: 200 MW | 500 | 600 | 274,160 |
| By year 2020: 400 MW | 1,000 | 600 | 548,320 |
| II. **Fuel Cell Vehicles (FCVs)** [2] | | | |
| By year 2015: 60,000 FCVs | 1,080 | 1,296 | 463,490 |
| By year 2020: 120,000 FCVs | 2,160 | 1,296 | 926,980 |

Notes:

1. Assumes installed capacity of Ontario's FCPPs will be 200MW by 2015, increasing by 40MW/yr to 400 MW by 2020, and to 600 MW by 2025. (Reference 13).

2. Assumes 60,000 FCVs on Ontario's roads by 2015, increasing by 12,000 FCVs/yr to 120,000 FCVs by 2020 and to 180,000FCVs by 2025.

3. Based on installed cost of $2,500 Cdn/kW for FCPPs, and $18,000 Cdn/FCV for fuel cell system, including storage, auxiliaries, etc. (References 4, 18, 21, 32).

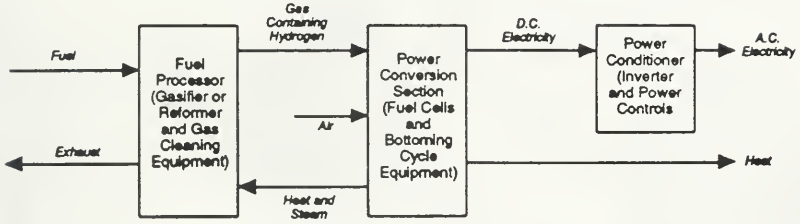
4. Assumes 60%Ontario content and employment generated by components manufactured in Ontario @ 10 jobs/$million economic activity; employment includes direct, indirect & induced jobs. (Reference 10).

5. Based on:
   - FCPPs @ 90% annual capacity, natural gas fuelled pressurized SOFC-GT @ conversion efficiency of 65% vs a natural gas fuelled advanced gas turbine (AGT) @ conversion efficiency of 40%. (References 17, 19)
   - For FCVs, hydrogen fuelled PEMFC vs a gasoline fuelled ICEV, based on 40,000 km/vehicle/yr, full fuel cycle emissions and $H_2$ produced by electrolysis of water - Ontario fuel mix. (References 2, 32, 36).
   - Oxidation of natural gas produces 49.0 g $CO_2$/MJ, or 176.4 kg $CO_2$/MWh.
   - Emissions from SOFC-GT (at 65% efficiency) include: 271.4kg $CO_2$/MWh, 0.03kg$NO_x$/MWh.
   - Emissions from AGT (at 40% efficiency) include: 441kg $CO_2$/MWh, 0.9kg$NO_x$/MWh, 3.4kg CO/MWh. (Reference 13).

## APPENDIX B

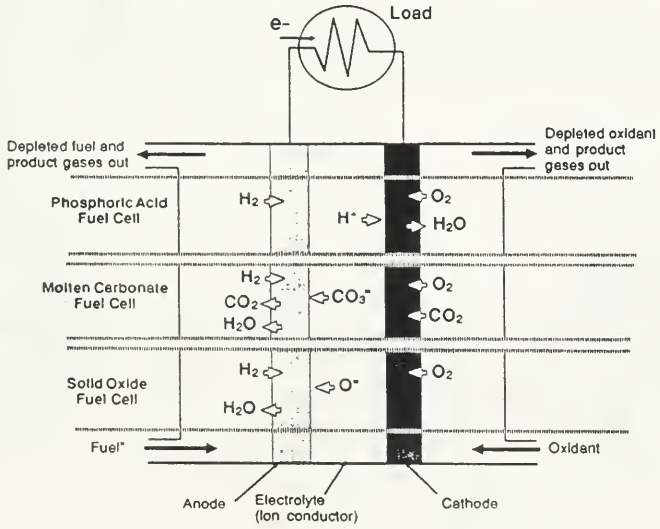
### EXHIBIT 1

### FUEL CELL POWER PLANT SCHEMATIC (Reference 24)




### EXHIBIT 2

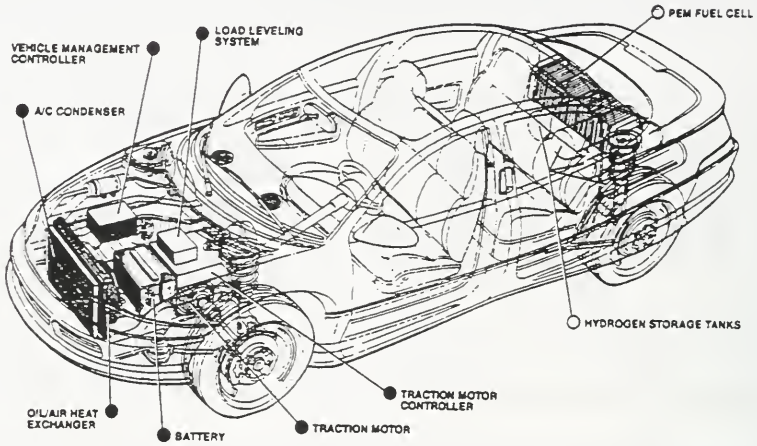
### ELECTROCHEMICAL REACTIONS FOR DIFFERENT FUEL CELLS (Reference 24)




* In the solid oxide and molten carbonate fuel cells, carbon monoxide in the fuel stream is also typically utilized as fuel.

## EXHIBIT 3

## CONCEPTUAL PEMFC VEHICLE ( Reference 29)




## EXHIBIT 4

## COMPONENTS OF THE FUEL CELL POWERED BUS ( Reference 28)

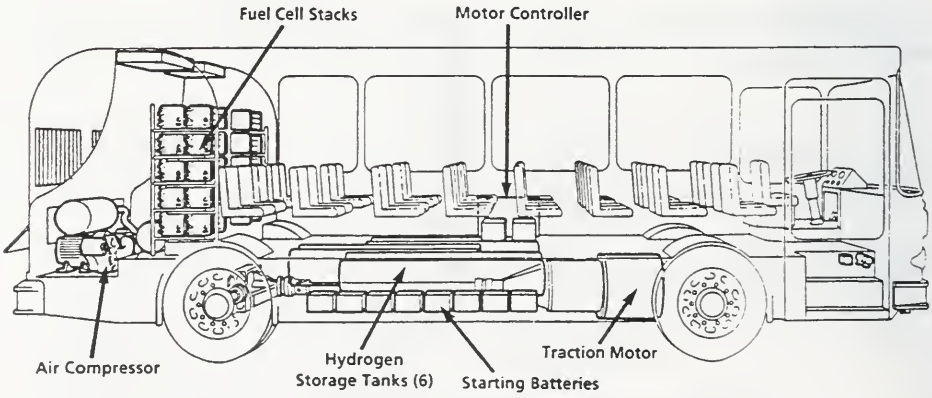
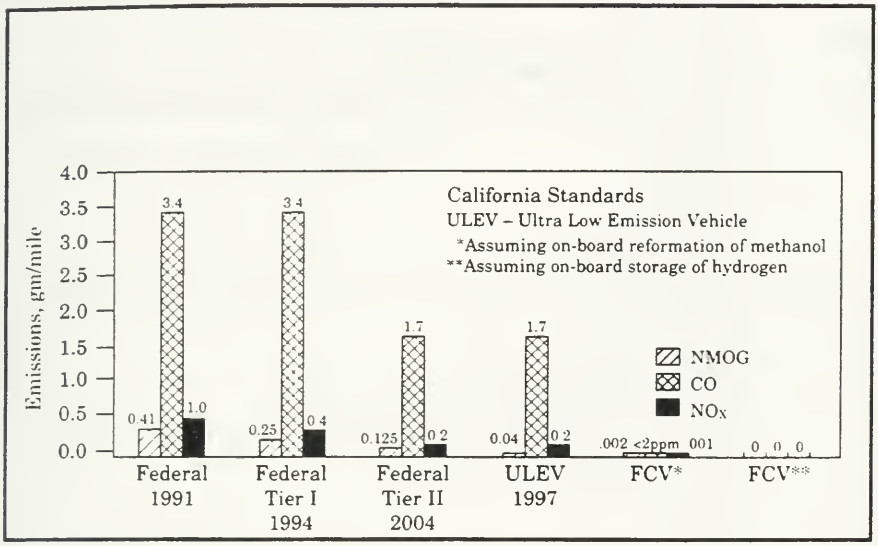


EXHIBIT 5

FUEL CELL TECHNOLOGY REDUCES AIRBORNE EMISSIONS OF POLLUTANTS FROM VEHICLES TO NEGLIGIBLE LEVELS, EVEN COMPARED TO RIGOROUS CALIFORNIA ULEV STANDARDS. (Reference 3)



## Appendix C

## Acronyms, Abbreviations and Definitions

| | |
|---|---|
| AAFC | Aluminum air fuel cell |
| AC | Alternating current |
| AFC | Alkaline fuel cell |
| °C | Degree Celsius |
| CO | Carbon monoxide |
| $CO_2$ | Carbon dioxide |
| CHES | Centre for Hydrogen and Electrochemical Studies, University of Toronto |
| DC | Direct current |
| DMAFC | Direct methanol air fuel cell |
| EPRI | Electric Power Research Institute |
| ESTCO | Electrochemical Science & Technology Centre, University of Ottawa |
| FCV | Fuel cell vehicle |
| GT | Gas turbine |
| $H_2$ | Hydrogen |
| HC | Hydrocarbons |
| HHV | Higher heating value |
| kW | kilowatt (1,000 watt) |
| kWh | kilowatt-hour |
| MW | Megawatt (1 million watt) |
| MWh | Megawatt-hour |
| MCFC | Molten carbonate fuel cell |
| $NO_x$ | Nitrogen oxides ( the sum of $NO_2$ and NO) |
| PAFC | Phosphoric acid fuel cell |
| PEMFC | Proton exchange membrane fuel cell |
| SOFC | Solid oxide fuel cell |
| tonne | 1,000 kg |
| ULEV | Ultra Low Emission Vehicle (refers to "tailpipe emissions" only) |
| VOCs | Volatile organic compounds |
| W | Watt |
| ZEV | Zero Emission Vehicle (refers to "tailpipe emissions" only) |

| | |
|---|---|
| Distributed generation | Distributed generation strategically places small, modular power generation units ( typically 100kW to 25 MW) close to electric power users. This helps improve operation of the existing grid and extends energy service cost effectively to customers. |
| Greenhouse gas | Any gas that absorbs infrared radiation in the atmosphere. A collective term for carbon dioxide, carbon monoxide, chlorofluorocarbons, ground-level ozone. methane, nitrogen oxides and VOCs. |
| Ground-level ozone | A colourless, highly irritating gas, formed primarily when two groups of air pollutants - $NO_x$ and VOCs - from industrial, automobile and other emissions - react in the presence of sunlight. |

# READER RESPONSE FORM

## Fuel Cells

## A Promising Technology For The Next Millennium

## 1999

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